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IN-FLIGHT HYPOXIA EVENTS IN TACTICAL JET AVIATION: CHARACTERISTICS COMPARED TO NORMOBARIC TRAINING

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hypoxia symptoms, reduced oxygen breathing device (ROBD), aerospace physiology, low-pressure chamber (LPC) training

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ABSTRACT

INTRODUCTION: Hypoxia continues to be a significant threat in military aviation. To counter the hypoxia threat, military jet aviators receive periodic training using a reduced oxygen breathing device (ROBD). This study explored the characteristics of in-flight hypoxia events among tactical jet aviators and compared reported symptoms to those experienced during normobaric (ROBD) training. **METHODS:** An anonymous survey was administered to aviators prior to naval aviation physiology training, which queried them about previous in-flight hypoxia encounters and the symptoms they experienced. This data was then compared to symptom data from a previous ROBD training survey using chi-square analyses. **RESULTS:** Of the 566 aviators who completed the survey, 112 (20%) reported experiencing hypoxia symptoms in a tactical jet aircraft. Forty-five (40%) occurred in the F/A-18, 38 (34%) occurred in the EA-6B, and the remaining 29 (26%) occurred in other platforms. Sixty-four aviators (57%) indicated that they were *not* wearing the required oxygen mask when the incident first occurred. The three most commonly reported in-flight hypoxia symptoms were tingling (54%), difficulty concentrating (32%), and dizziness (30%). Chi-square analyses revealed differences between the five symptoms encountered in-flight and those experienced during ROBD training.
DISCUSSION: The present investigation is the first survey-based study of hypoxia events in U.S. naval aviation. This study reveals only 21% of hypoxia events were reported in aviation hazard reports, and 57% of hypoxia events occurred with the oxygen mask off. In-flight, mask-on hypoxia has a similar overall symptom profile to ROBD training, but significant differences exist between five individual symptoms.

KEYWORDS: hypoxia symptoms; reduced oxygen breathing device; aerospace physiology; ROBD

INTRODUCTION:

In 1862, James Glaisher and Henry Coxwell became the first humans to ascend over 8,839 m (29,000 ft); they made this historic ascent in an open hot-air balloon. The hypoxia they experienced at this altitude nearly killed them. Glaisher's record of this near-death experience in his monograph, *Travels in the Air*, was one of the first accounts of hypoxia in aviation (7). Over the next 100 years, hypoxia remained a serious threat to aviation safety. Scientists in the early 1960s attempted to characterize the various physiologic effects of hypoxia to better understand the threat to aviators (3, 4). As understanding of hypoxia grew, efforts were made to prevent hypoxia-induced aircraft mishaps. In addition to oxygen breathing systems and pressurization of crew and passenger compartments, hypoxia-warning systems were developed and implemented (10, 11). In spite of these strides, 417 incidents of hypoxia with 30 cases of unconsciousness were reported in the U.S. Air Force between 1963 and 1970 (8).

The U.S. military introduced physiologic training for aviators during this early period of growing hypoxia awareness. The goal was to familiarize aviators with hypoxia symptoms in a controlled environment, so they might better recognize its onset in flight. Hypoxia familiarization instruction remains a vital component of aviator training in the U.S. military and is also used extensively in other countries (9). Military aviators receive initial hypoxia familiarization training in a low-pressure chamber (LPC) as part of their preflight indoctrination. These aviators then receive subsequent, periodic refresher training. This type of hypoxia training conventionally exposes aviators to simulated altitudes of 7620 m (25,000 ft) through reduced barometric pressure in a LPC. Participants remove their oxygen masks and perform various psychomotor activities, while at simulated altitude, to familiarize themselves with their personal hypoxia symptoms.

Researchers have analyzed in-flight incidents and have found hypoxia to be more likely to occur in training aircraft or tactical jet platforms while wearing an oxygen mask (5, 13). These researchers suggested alternative, mask-on approaches, particularly for refresher training of tactical jet aviators who have already received initial training in the LPC. The U.S. Navy responded to this call for more relevant hypoxia training and incorporated the reduced oxygen breathing device (ROBD) into training to induce hypoxia using mixed gas delivered through an aviator's oxygen mask. This training was developed for the most at-risk aviators who fly high-performance jet aircraft.

The ROBD simulates the diminished oxygen, which is present at higher altitudes, by mixing breathing air and nitrogen under sea level (normobaric) conditions. Both first- and second-generation ROBDs have been found capable of consistently reproducing the cognitive and physiologic effects of high-altitude hypoxia at sea level. Furthermore, second-generation devices demonstrated that the objective and subjective effects of hypoxia, induced at sea level (ROBD), are comparable to those experienced under reduced barometric pressure (LPC) (14-16).

These initial validation studies with ROBD were further tailored for operational implementation. Artino, Folga, and Swan (1) conducted an instructional evaluation of a new hypoxia-training paradigm, which paired a second-generation ROBD (ROBD-2) with high fidelity F/A-18 flight simulators. Symptomatic findings from this study and a follow-on investigation indicated air hunger, difficulty concentrating, and dizziness were the most common hypoxia symptoms reported during training (2). These particular results elevated the investigators' concern that the hypoxia symptoms experienced during ROBD-2 training may be different than those experienced by aviators during actual in-flight hypoxia incidents. Such differences, if they do exist, are important because they challenge the extent to which hypoxia training transfers to the operational environment. A subsequent software change increased

ROBD-2 mask flow rate from 30 to 50 liters per minute (LPM) to more accurately mimic the characteristics of familiar jet aircraft breathing systems. The validity of this new iteration of ROBD-2, with increased mask flow, has not been studied in detail.

Fatal flight mishaps in the military, though considered infrequent, are costly and preventable. The U.S. Navy has experienced three fatal flight mishaps attributable to hypoxia since 2001 (12). As such, hypoxia training continues to be a vital part of military aviation safety. The present study represents the continuation of several investigations designed to validate and further improve normobaric hypoxia training in military aviation (1, 2, 14-16). Increased understanding of in-flight hypoxia and further improvements in hypoxia training will result in safer and more effective aviators. The purpose of this study was to characterize in-flight hypoxia events and compare these characteristics to the hypoxia symptoms reported by aviators trained on the new ROBD-2 upgrade (50 LPM) [1].

METHODS:

Research Design:

This study is a retrospective, non-experimental design of preexisting anonymous survey data. The Naval Survival Training Institute (8) collected this data as part of their education and training mission, as mandated by the Chief of Naval Operations. This "on the shelf" data was collected in the context of NSTI's Naval Aviation Survival Training Program (NASTP). The data consisted of two sets of completed surveys. Survey responses did not contain any personally identifiable information, and Institutional Review Board exemption was obtained through the Uniformed Services University of Health Sciences.

[1] For simplicity, the ROBD-2 upgrade (i.e., the 50 LPM ROBD-2 device) will be referred to as the ROBD-2 for the remainder of this article.

Study Population:

The study population was comprised of two sets of survey participants who were enrolled in NASTP training. These participants included a total of 722 aviators who received hypoxia training using the ROBD-2 in combination with either a high or low-fidelity, non-motion-based flight simulator. The training was conducted in accordance with NASTP standard operating procedures. All participants were instructed that completion of the surveys was voluntary and their anonymity would be preserved. No personally identifiable information was collected on study participants.

Survey Data Collection:

Two groups of aviators, participating in refresher NASTP training, received normobaric hypoxia training: Group 1 (n = 566) completed an anonymous, 20-item survey (Survey A) *prior to* ROBD-2 training. Group 2 (n = 156) completed an anonymous, 19-item survey (Survey B) *following* ROBD-2 training. All aviators surveyed were completing aerospace physiology recertification for tactical aviation platforms. These anonymous surveys were designed by NSTI to assess various aspects of ROBD-2 training and actual in-flight hypoxia events.

Survey A (20-item, *pre-training* survey): The first portion of the survey was composed of demographics items, as well as several dichotomous items (yes-no) that asked participants about their previous experiences with actual in-flight hypoxia events. Participants were then provided a list of 16 symptoms of hypoxia commonly described in the literature (6). Respondents were asked to identify the symptoms experienced during their reported in-flight hypoxia incidents.

Survey B (19-item, *post-training* survey): The initial portion of this survey was composed of demographics items, as well as an individual item that asked participants to rate the quality of the training. The second part of the survey provided participants with the same list of 16 symptoms of hypoxia as Survey A, and they were asked to identify the symptoms they experienced during ROBD-2 training.

Survey results from Group 1 (pre-training survey) were compared to survey results from Group 2 (post-training survey). In particular, the hypoxia symptoms experienced by a sample of aviators in flight (Group 1) were compared to the symptoms experienced by a different sample of aviators during ROBD-2 training (Group 2).

Data Analysis:

Data from the surveys were coded and analyzed using SPSS 16.0. The 16 symptoms reported during in-flight hypoxia incidents were characterized using descriptive statistics. Differences in the 16 hypoxia symptoms experienced by aviators in Group 1 (previous, in-flight hypoxia) and the 16 hypoxia symptoms experienced by aviators in Group 2 (ROBD-2 training) were compared using chi-square analysis (alpha=0.05), Fischer's exact test (alpha=0.05), and incident risk ratios, as appropriate.

RESULTS:

Characteristics of In-Flight Hypoxia

Of the 566 aviators in Group 1 who completed Survey A, there were 543 (96%) males and 23 (4%) females (see Table I). The average age was 33 years (*SD* = 6), and the average number of flight hours reported was 1,453 hours (*SD* = 952). The sample consisted of 340 (60%) pilots and 218 (39%) naval flight officers.

[Insert Table I about here]

Of the 566 aviators in Group 1, 112 (20%) reported experiencing hypoxia symptoms in flight. Among these, 45 (40%) occurred in the F/A-18 Hornet, 38 (34%) occurred in the EA-6B

Prowler, and the remaining 29 (26%) occurred in other aviation platforms (see Table II). Altogether, the reported hypoxia incidents occurred at a mean aircraft altitude of 7,640 m (25,064 ft) mean sea level (*SD* = 2,570 m [8,433 ft], and 64 aviators (57%) indicated that they were *not* wearing an oxygen mask when the incident first occurred. Taken together, the three most commonly reported in-flight hypoxia symptoms were tingling (54%), difficulty concentrating (32%), and dizziness (30%). See Figure 1 for complete frequency list of symptoms reported.

[Insert Table II & Figure 1 about here]

To further explore the characteristics of in-flight hypoxia, aviators in Group 1 who reported experiencing hypoxia were sub-divided into two groups: “mask-on” and “mask-off” hypoxia. In this analysis, pilots represented 85% of reported mask-on events, but they comprised only 41% of mask-off events (see Table III). The mean aircraft altitude of mask-on events was 8,274 m (27,147 ft) mean sea level (*SD* = 2,922 m [9,585 ft]), and the mean altitude of mask-off events was 7,173 m (23,534 ft) mean sea level (*SD* = 2,187 m [7,175 ft]).

[Insert Table III about here]

ROBD-2 Training vs. In-Flight, Mask-On Events

Chi-square and Fischer’s exact test analyses were conducted as appropriate; this analysis compared symptoms reported during ROBD-2 training (as reported on Survey B) to in-flight, mask-on hypoxia symptoms reported on Survey A. Of the 16 symptoms queried and analyzed with the chi-square test for independence, five were determined to have reported frequencies that were statistically different ($p < 0.05$). The remaining 11 symptoms were not statistically significantly different between those trained on the ROBD-2 and the in-flight respondents (p >

0.05; see Figure 1). Although multiple comparisons were conducted in this analysis, a Bonferroni correction was not used (i.e., it was deemed to be a less conservative approach).

Incidence risk ratios (IRRs) were also calculated and graphed with 95% confidence intervals (see Figure 2). This analysis was conducted to provide a gestalt of the entire data set. Two symptoms, lights dimming and cold flash, were not included in this analysis due to extremely low reporting among in-flight, mask-on hypoxia respondents. Symptom-specific IRRs greater than 1.0 indicate higher incidence among ROBD-2 respondents, and IRRs less than 1.0 indicate greater incidence among in-flight respondents. An IRR of exactly 1.0 would indicate identical incidence between ROBD-2 and in-flight respondents. Of the 14 symptoms examined, 9 had higher incidence among ROBD-2 respondents, with air hunger emerging with the highest IRR (2.3).

[Insert Figure 2 about here]

DISCUSSION:

Hypoxia Prevalence and Reporting

The present investigation is the first survey-based study of hypoxia events in U.S. naval aviation; the design allowed for an assessment of the prevalence of hypoxia experienced in the operational tactical aviation setting. Twenty percent of respondents reported experiencing a hypoxia event while flying; this observation is significant and sobering. Hypoxia continues to be a considerable threat to modern military aviation, despite much effort to prevent it and mitigate its effects. Other studies have examined hypoxia events from hazard report (HAZREP) data submitted to military safety centers; however, the current study reveals only 21% of hypoxic events are reported in HAZREPs. This finding suggests hypoxia is considerably under-reported in tactical naval aviation.

Mask-On versus Mask-Off Hypoxia and Training

Navy regulations require oxygen masks to be worn at all times from take-off to landing in tactical platforms. This study reveals 57% of hypoxia events in these platforms occur with the oxygen mask off. This result suggests mask-off hypoxia is more common than previously described (5). Thirty-seven of 44 naval flight officers (NFOs) who reported hypoxia had their masks off at the time of their events. Though more pervasive among NFOs, 41% of all mask-off events were reported by pilots. Ninety-two percent of incidents occurring in the EA-6B were with the mask off, and the majority of these incidents were reported by NFOs. Of note, only 14% of mask-off incidents were reported in a HAZREP, whereas 31% of mask-on events were reported. This discrepancy is likely influenced by the recognized and unreported violation of mask-off flight. Although multiple factors may contribute to hypoxia events going unreported; aviators' reluctance to "put themselves on report" should also be considered. The relatively low number of hypoxia HAZREPs appears to under-represent the true prevalence of hypoxia events in naval aviation. Such under-reporting results in a misperception of hypoxia's true threat and may contribute to a sense of false security among tactical jet aviators. Decreased mask use coupled with unreported hypoxia events perpetuates a dangerous yet preventable risk in this population. Increased compliance of Navy regulations is undoubtedly needed. In particular, oxygen masks must be worn, and HAZREPs must be filed.

Efforts to increase mask compliance in naval aviation should be complemented with training. Current false securities can be combated with informed training, which emphasizes mask use and HAZREP reporting. Results from this study should be communicated to tactical jet aviators in hypoxia training. ROBD-2 is a valuable adjunctive to hypoxia training, but the relevance of mask-on training is predicated on oxygen masks being worn in flight. We must fight like we train, if we aim to train like we fight.

In-Flight Mask-On versus ROBD Symptoms

Mask-on hypoxia has a similar overall symptom profile to ROBD-2, but significant differences exist between individual symptoms. Five of the 16 queried symptoms differed statistically in reporting patterns. Four of these five symptoms were among the most frequently reported in *both* ROBD-2 and in-flight, mask-on hypoxia events. These similar reporting trends (see Figure 1) suggest congruence between ROBD-2 and in-flight, mask-on hypoxia symptoms.

Air hunger has been identified as a particularly common symptom in ROBD-2 training, though its prevalence has been reduced through the use of the ROBD-2 (50 LPM) upgrade (2). The present comparison reveals air hunger remains statistically different from actual, in-flight, mask-on events. If technically feasible, one solution may be to increase the gas-flow rate above the current 50 LPM to address this persistently high report of air hunger. However, such a change must be balanced with the engineering parameters of this system.

The authors recommend the continued use of ROBD-2 as a valid and operationally relevant training tool. Hands-on ROBD training should be augmented with a data-driven discussion of its fidelity to actual in-flight events. Trainees should be apprised of both the similarities and potential differences in the two symptom profiles. Further study of the potential differences between ROBD-2 and in-flight symptom profiles will better inform this discussion and should lead to improved training with ROBD-2. Additionally, a study comparing LPC symptoms to in-flight, mask-off hypoxia symptoms may also be warranted.

Study Limitations

There are several important limitations in the current study. First, this study relied on self-reported data, which has many limitations, including recall and social desirability bias. Due to perceived unfavorable admission, it is reasonable to assume the current data under-represent the true incidence of hypoxia in-flight. This is a frightening assumption, considering the high incidence of in-flight hypoxia reported by participants in this study. Also, the circumstances and symptoms reported during in-flight events are subject to recall bias; actual characteristics of the events may have been different than those reported (e.g., altitude and exact symptoms). Further, the reported in-flight hypoxia events cannot be verified as actual clinical cases of hypoxia and, more importantly, some may have been cases of *hyperventilation*, which can mimic hypoxia symptoms. Unfortunately, there are no standard physiologic measures of hypoxia currently used in operational military aviation. This absence of surveillance makes it impossible to know the actual prevalence of hypoxia during flight operations.

Second, though sampled from several NSTI sites over a one-year period, these results may not be representative of the overall tactical naval aviation community. Therefore, the generalizability of these results is limited to individuals flying similar platforms and with similar demographic and professional flying histories.

Third, the comparison between ROBD-2 and in-flight data was based on frequencies of symptoms within the samples surveyed, and not matched by individual. It would be ideal to perform a by-participant comparison of ROBD-2 and subsequent in-flight events, but considering the unforeseen nature of in-flight hypoxia, this approach would be difficult (if not impossible) to implement.

Summary

Hypoxia is a significant and largely preventable aeromedical threat in tactical naval aviation. This study reveals potential opportunities to reduce this threat through increased adherence to Navy regulations (mask use), increased reporting of hypoxia incidents, and improved hypoxia-training modalities. Further study of the potential differences between in-flight hypoxia and training hypoxia should be conducted to improve training fidelity. Realized improvements will more effectively equip aviators who experience acute hypoxia to recognize it, recover from it, and return home safely.

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Table I. TOTAL SAMPLE DEMOGRAPHICS BY FLEET AIRCRAFT TYPE.

							Gender				*Crew Position*					
			Flight Hours		Age		Male		Female		*Pilot*		*NFO*		*Other*	
Aircraft	*n*	(%)*	*M*	(*SD*)	*M*	(*SD*)	*n*	(%)	*n*	(%)	*n*	*(%)*	*n*	*(%)*	*n*	*(%)*
Total Sample	566	(100)	1,453	(952)	33.0	(6.0)	543	(96)	23	(4)	340	(60)	218	(39)	8	(1)
F/A-18	259	(46)	1,639	(990)	33.0	(6.0)	255	(98)	4	(2)	207	(80)	51	(19)	1	(1)
EA-6B	209	(37)	1,202	(842)	32.0	(6.0)	191	(91)	18	(9)	64	(31)	143	(68)	2	(1)
EA-18G	29	(5)	1,743	(1,010)	34.0	(6.0)	28	(97)	1	(3)	12	(41)	17	(59)	0	(0)
AV-8B	38	(7)	1,154	(810)	32.0	(6.0)	38	(100)	0	(0)	38	(100)	0	(0)	0	(0)
Other A/C	23	(4)	1742	(965)	38.0	(9.0)	23	(100)	0	(0)	14	(61)	5	(22)	4	(17)

Table II. REPORTED HYPOXIA EVENT CHARACTERISTICS BY HYPOXIA AIRCRAFT TYPE.

							Crew Position						Hypoxia Mode									
Hypoxia Aircraft			Age		Flight Hours		Pilot		NFO		Other		Mask-On		Mask-Off		Altitude (ft)		Performed EP		Reported HazRep	
	n	(%)	*M*	(*SD*)	*M*	(*SD*)	*n*	(%)	*n*	(%)	*n*	(%)	*n*	(%)	*n*	(%)	*M*	(*SD*)	*n*	(%)	*n*	(%)
All A/C	112	(100)	35.0	(6.0)	1,914	(958)	67	(60)	44	(39)	1	(1)	48	(43)	64	(57)	25,064	(8,433)	107	(96)	24	(21)
F/A-18	45	(40)	35.0	(4.0)	1,960	(718)	36	(80)	9	(20)	0	(0)	31	(69)	14	(31)	27,795	(8,174)	42	(93)	12	(27)
EA-6B	38	(34)	34.0	(4.0)	1,654	(700)	12	(32)	26	(68)	0	(0)	3	(8)	35	(92)	22,742	(6,011)	37	(97)	6	(16)
F-14	7	(6)	42.0	(6.0)	3,407	(1,055)	2	(29)	5	(71)	0	(0)	2	(29)	5	(71)	23,571	(7,067)	7	(100)	0	(100)
T-45	7	(6)	31.0	(6.0)	1,251	(1,080)	7	(100)	0	(0)	0	(0)	7	(100)	0	(0)	28,630	(16,973)	6	(86)	1	(14)
Other A/C	15	(14)	38.0	(8.0)	2,054	(1,338)	10	(67)	4	(27)	1	(7)	5	(33)	10	(67)	21,967	(7,575)	15	(100)	5	(33)

Table III. REPORTED HYPOXIA EVENT CHARACTERISTICS BY HYPOXIA MODE (MASK-ON/MASK-OFF).

Hypoxia			Age		Flight Hours		Crew Position: Pilot		Crew Position: NFO		Crew Position: Other		No. of Events			Altitude (ft)		Performed EP		Reported HazRep	
Mode	*n*	(%)	*M*	(*SD*)	*M*	(*SD*)	*n*	(%)	*n*	(%)	*n*	(%)	1	2	3	*M*	(*SD*)	*n*	(%)	n	(%)
Mask-On	48	(43)	36.0	(5.0)	2,167	(1,019)	41	(85)	7	(15)	0	(0)	37	7	1	27,147	(9,585)	44	(92)	15	(31)
Mask-Off	64	(57)	35.0	(6.0)	1,732	(876)	26	(41)	37	(59)	1	(2)	48	12	4	23,534	(7,175)	63	(98)	9	(14)

Figure Captions:

Fig. 1. Hypoxia Symptoms (%): In-Flight, Mask-On Incident vs. ROBD Training. Symptoms annotated with (*): Tingling, Difficulty Concentrating, Air Hunger, Blurred Vision, and Lights Dimming were statistically different ($p < 0.05$).

Fig. 2. Incidence Risk Ratios (IRR) Comparing ROBD to In-Flight, Mask-On Symptoms with 95% Confidence Intervals. Data points above 1 indicate higher incidence in ROBD, whereas those below 1 indicate higher incidence among in-flight. An IRR = 1 indicates equal incidence among ROBD and in-flight respondents. (Lights dimming and cold flash were not included in this analysis due to extremely low reporting among in-flight hypoxia respondents.)

Fig. 1.

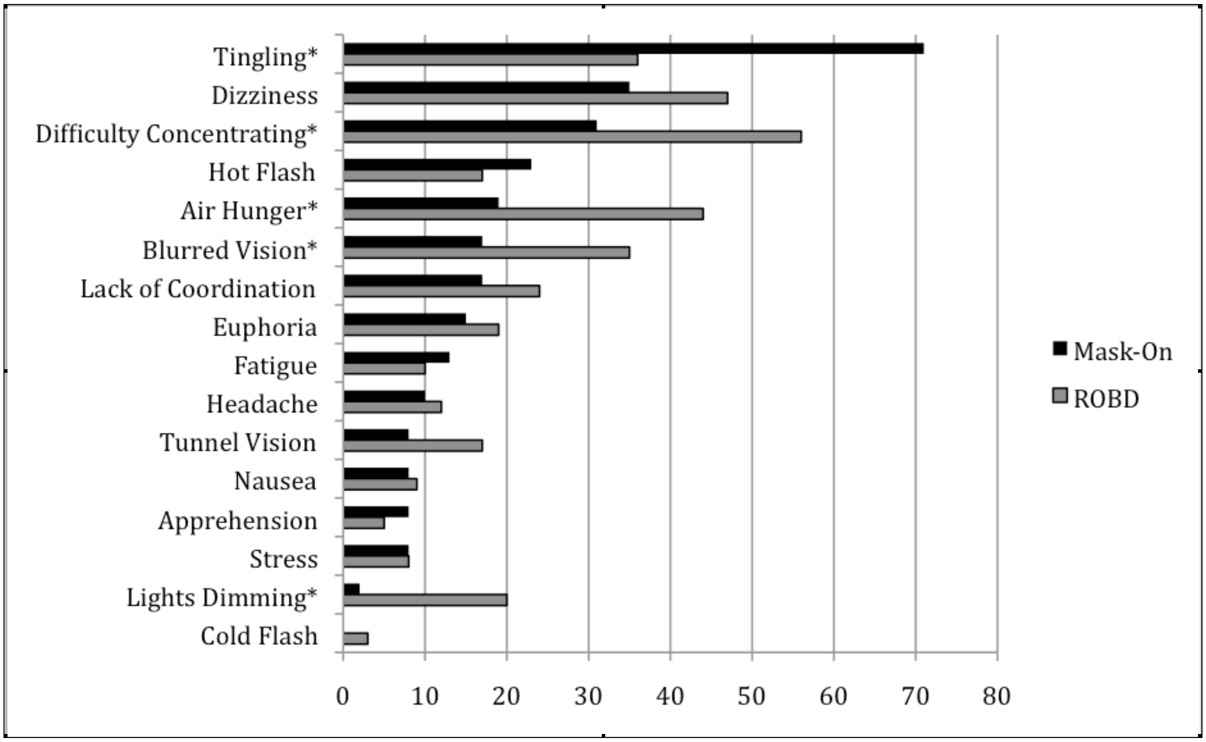
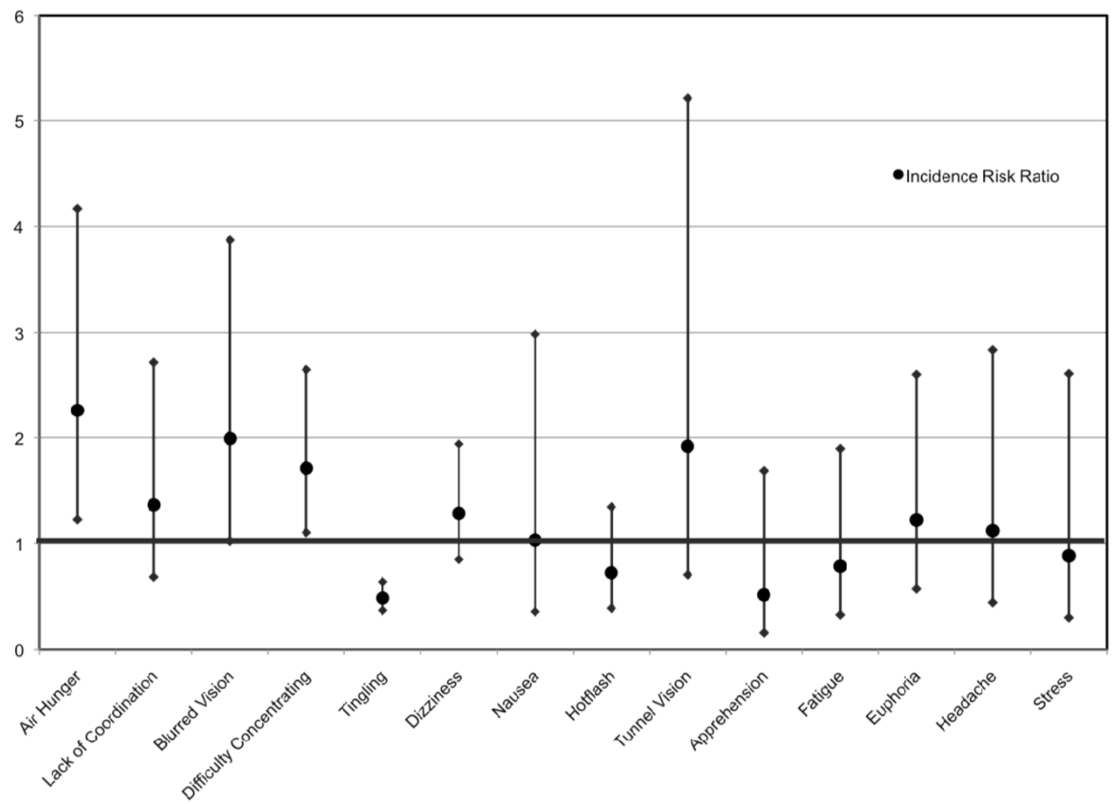

Tingling*
Dizziness
Difficulty Concentrating*
Hot Flash
Air Hunger*
Blurred Vision*
Lack of Coordination
Euphoria
Fatigue
Headache
Tunnel Vision
Nausea
Apprehension
Stress
Lights Dimming*
Cold Flash
0
10
20
30
40
50
60
70
80
Mask-On
ROBD

Fig. 2.


6
5
4
3
2
1
0
Incidence Risk Ratio
Air Hunger
Lack of Coordination
Blurred Vision
Difficulty Concentrating
Tingling
Dizziness
Nausea
Hotflash
Tunnel Vision
Apprehension
Fatigue
Euphoria
Headache
Stress